

SUBSTITUTE SPECIFICATION (Marked-Up)

A-METHODS OF ESTIMATING PRECIPITATION CHARACTERISTICS

Related Application

[0001] This is a §371 of International Application No. PCT/FR2004/002692, with an international filing date of October 21, 2004 (WO 2005/040853 A1, published May 6, 2005), which is based on French Patent Application No. 03/12299, filed October 21, 2003.

Technical Field

[0002] ~~The present~~This invention relates to ~~a-methods~~ of estimating precipitation characteristics and, in one particular aspect, precipitation rate for solid precipitation.

Background

[0003] It is known ~~from the state of the art~~ that the characteristics of a radar image can be used to estimate rainfall characteristics. In particular, ~~European Patent~~ EP 1 049 944 describes a technique for estimating rainfall using a radar. In that patent, provision is made for the following steps:

[[ - ]] using ~~that a~~ dual-polarized radar to measure the differential phase shift ( $\Phi_{dp}$ ) and the apparent reflectivity  $Z$  in at least one of the H (horizontal) or V (vertical) polarizations and over a given range  $\{(r_o, r_i)\}$  of path radii relative to ~~said~~the radar;

[[ - ]] determining an estimate of the value  $No^*$  representative of the size distribution of the rain drops, on the basis of the differential phase shift difference over the range  $r_o$  to

$r_i$ , and on the basis of an integral of a function of the apparent reflectivity  $Z$ , over the range  $\{r_0, r_i\}$ ; and

[[ - ]] deducing the value of the precipitation rate at a point on the basis of  $No^*$  and of the apparent reflectivity at ~~said~~the point.

[0004] A method of estimating rainfall is also known from ~~PCT-Patent~~ WO\_03/007016, which describes a method of estimating a precipitation rate by means of a dual-polarized radar, that method being characterized by the following steps:

[[ - ]] using ~~that a~~ dual-polarized radar to measure the differential phase shift  $\Phi_{dp}$  and ~~the~~ attenuated reflectivity  $Z$  in at least one of the H or V polarizations and over a given range  $\{r_1, r_0\}$  of path radii  $r$  relative to ~~said~~the radar;

[[ - ]] determining an estimate of the value  $K(r_0)$  of the specific attenuation at  $r_0$  on the basis of the profile of the attenuated reflectivity measured in this way, and on the basis of the differential phase shift difference over the range  $r_0$  to  $r_1$ ; determining an estimate  $K(r)$  of the specific attenuation at  $r$  as a function of the attenuation  $K(r_0)$  determined in this way and of the attenuated reflectivity profile  $Z(r)$ ; and determining the precipitation rate  $R(r)$  once  $K(r)$  is known.

[0005] Those various solutions make it possible to characterize liquid precipitation and to estimate precisely rainfall rate (in millimeters per hour (mm/h), but they do not make it possible to estimate the characteristics of solid precipitation such as snow.

### Summary

[0006] This invention relates to a method of estimating precipitation characteristics including acquiring a radar image including at least a vertical plane of a precipitation zone, processing a

vertical profile to generate digital signals representative of reflectivity in vertical direction z, integrating the signals representative of reflectivity by assimilation of a reflectivity vertical profile in an aggregation model to generate a signal representative of the profile in the vertical plane of a mean particle diameter weighted by mass of each particle, and determining concentration of the solid particles on the basis of signals previously determined.

~~{0007}—An object of the invention is to provide a novel method that remedies that drawback.~~

~~{0008}—To this end, and in its most general acceptance, the invention provides a method of estimating precipitation characteristics and in particular precipitation rate for solid precipitation, said method comprising an acquisition and processing step consisting in acquiring a radar image including at least a vertical plane of a precipitation zone, and in processing a vertical profile so as to deliver digital signals representative of reflectivity in the vertical direction h, said method being characterized in that it further comprises an integration step consisting in integrating said signals representative of reflectivity so as to deliver a signal representative of the profile in the vertical plane of a the mean particle diameter weighted by the mass of each particle, and a determination step consisting in determining the concentration of the solid particles on the basis of the signals computed in the preceding steps.~~

~~{0009}—Preferably, the integration step consists in determining the variable Z(h) of the radar observable in mm<sup>6</sup>/m<sup>3</sup> as a function of the altitude h on the basis of said radar image, and in determining said mean diameter D<sub>m</sub>(h) of the particles by resolving the following equation:~~

$$\frac{fD_m}{fh} = 0.25k_{eff}aD_m^{b-5} 10^{-18}Z + \left( \frac{1}{6} \frac{fZ}{Zfh} \right) D_m \quad (2)$$

where:

Z is the radar observable to be inverted in mm<sup>6</sup>m<sup>-3</sup>;

D<sub>m</sub> is in meters (m);

~~$a$  and  $b$  are coefficients specific to particles of the “aggregate” type; for example, the coefficient  $a$  is equal to 35184 and the coefficient  $b$  is equal to 3.16;~~

~~$k_{eff}$  is the coefficient of effectiveness of the aggregation process to be adjusted, said coefficient  $k_{eff}$  being equal to 0.3.~~

~~[00010]—Integration of (2) requires an integration boundary condition. Advantageously, said integration boundary condition is determined so that the value  $D_m(h)$  at the top of the cloud corresponds to the predetermined value for the total number of particles at the top of the cloud.~~

~~[00011]—In an advantageous implementation, the profile of the total number of particles  $n_t(h)$  is determined by the following equation:~~

$$n_t(h) = x \cdot Z(h) / D_m(h)^6$$

~~where  $x$  is equal to  $25.4 \cdot 10^{-18}$ ;~~

~~[0010]—In another implementation, the meteorological parameter  $N_0(h)$  is determined by the following equation:~~

$$N_0(h) = y \cdot Z(h) / D_m(h)^7$$

~~where  $y$  is equal to  $102 \cdot 10^{-18}$ ;~~

~~[0011]—In a third implementation, the meteorological parameter corresponding to the profile of the ice water content  $IWC(h)$  (in  $g/m^3$ ) is determined by the following equation:~~

$$IWC(h) = w \cdot Z(h) / D_m(h)^3$$

~~where  $w$  is equal to  $1.25 \cdot 10^{-12}$ ;~~

~~[0012]—In a fourth implementation, the meteorological parameter corresponding to the profile of the solid precipitation rate  $R(h)$  (mm/h equivalent melted) is determined by the following equation:~~

$$R(h) = r \cdot Z(h) / D_m(h)^{2.35}$$

where  $r$  is equal to  $4.698 \cdot 10^{-10}$ ;

### Brief Description of the Drawings

[0013] ~~The~~Selected aspects of the invention will be better understood on reading the following description, given with reference to a non-limiting ~~implementation example and selected~~graphic representations below:

~~Figure 1 shows an example~~Fig. 1 is a graph of a vertical profile of Z to be inverted (in this example, the isotherm 0°C is at ground level);

~~Figure 2 shows the~~Fig. 2 is a graph of a profile of Dm resulting from Z being inverted by the aggregation model compared with ~~the~~a conventional estimator;

~~Figure 3 shows the~~Fig. 3 is a graph of profiles of N0 and of nT resulting from Z being inverted by the aggregation model compared with ~~the~~a conventional hypothesis and observations;

~~Figure 4 shows~~Fig. 4 is a graph of the vertical profile of Z to be inverted;

~~Figure 5 shows~~Fig. 5 is a graph of the profile of Dm resulting from Z being inverted by the aggregation model compared with the conventional estimator;

~~Figure 6 shows~~Fig. 6 is a graph of the profiles of N0 and nT resulting from the Z being inverted by the aggregation model compared with ~~the~~a conventional hypothesis and observations;

~~Figure 7 shows~~Fig. 7 is a graph of the profile of R resulting from Z being inverted by the aggregation model compared with ~~the~~a conventional estimator;

~~Figure 8 shows~~Fig. 8 is a graph of the sensitivity of the retrieval of the equivalent precipitation rate (mm/h) to the particle density law  $\rho(D) \propto D^{-\gamma}$ ; and

~~Figure 9 shows~~ Fig. 9 is a graph of the sensitivity of the retrieval of the vertical Doppler velocity to the particle density law  $\rho(D) \propto D^{-\gamma}$ .

### Detailed Description

[0014] This disclosure provides methods of estimating precipitation characteristics and, in a particular selected aspect, a precipitation rate for solid precipitation, the method comprising an acquisition and processing step comprising acquiring a radar image including at least a vertical plane of a precipitation zone, and in processing a vertical profile to deliver digital signals representative of reflectivity in the vertical direction h, an integration step comprising integrating signals representative of reflectivity to deliver a signal representative of the profile in the vertical plane of a mean particle diameter weighted by the mass of each particle, and a determination step comprising determining the concentration of the solid particles on the basis of the signals computed in the preceding steps.

[0015] Reference will be made to the drawings below as appropriate. Steps in accordance with selected aspects of the method may be seen in one sense by reference to Figs. 1 – 3.

[0016] In a preferred aspect, the integration step comprises determining the variable  $Z(h)$  of the radar observable in  $\text{mm}^6/\text{m}^3$  as a function of the altitude h on the basis of the radar image, and determining the mean diameter  $D_m(h)$  of the particles by solving the following equation:

$$\frac{fD_m}{fh} = -0.25k_{\text{eff}}aD_m^{-0.5} 10^{-18}Z + \left( \frac{1}{6} \frac{fZ}{Zfh} \right) D_m \quad (2)$$

where:

Z is the radar observable to be inverted in  $\text{mm}^6\text{m}^{-3}$ ;

$D_m$  is in meters (m);

$a$  and  $b$  are coefficients specific to particles of the “aggregate” type; for example, the coefficient  $a$  is equal to 35184 and the coefficient  $b$  is equal to 3.16;

$k_{eff}$  is the coefficient of effectiveness of the aggregation process to be adjusted, said coefficient  $k_{eff}$  being equal to 0.3.

Integration of (2) uses an integration boundary condition. Advantageously, the integration boundary condition is determined so that the value  $D_m(h)$  at the top of the cloud corresponds to the predetermined value for the total number of particles at the top of the cloud.

In an advantageous implementation, the profile of the total number of particles  $n_t(h)$  is determined by the following equation:

$$\underline{n_T(h) = x.Z(h)/D_m(h)^6}$$

where  $x$  is equal to  $25.4 \cdot 10^{-18}$ .

In another implementation, the meteorological parameter  $N_O(h)$  is determined by the following equation:

$$\underline{N_O(h) = y.Z(h)/D_m(h)^7}$$

where  $y$  is equal to  $102 \cdot 10^{-18}$ .

In another aspect, the meteorological parameter corresponding to the profile of the ice water content  $IWC(h)$  (in  $g/m^3$ ) is determined by the following equation:

$$\underline{IWC(h) = w.Z(h)/D_m(h)^3}$$

where  $w$  is equal to  $1.25 \cdot 10^{-12}$ .

In yet another aspect, the meteorological parameter corresponding to the profile of the solid precipitation rate  $R(h)$  (mm/h equivalent melted) is determined by the following equation:

$$\underline{R(h) = r.Z(h)/D_m(h)^{2.35}}$$

wherein  $r$  is equal to  $4.698 \cdot 10^{-10}$ .

[0017] The method applies ~~essentially~~ to stratiform precipitation. It considers that ~~the ice-~~ forming nuclei are activated ~~only~~ at highly negative temperatures, i.e., at the top of the cloud. ~~The ice~~Ice crystals formed at high altitude settle and grow as they fall, either by sublimation of the ambient saturating water vapor, or by collection and freezing of supermelted cloud water droplets, or ~~else~~ by random aggregation of their collisions with other ice crystals. Of the three growth processes, only aggregation changes the ice particle concentration. The characterization method is based ~~essentially~~ on a simplified description of the aggregation mechanism. ~~The in-~~ ~~vention is based on~~ We use a class of “profiler” methods ~~in that it~~ inverts the vertical profile of reflectivity measured in the ice, ~~so as~~ to extract therefrom the vertical profile of the solid precipitation rate.

[0018] ~~The~~Selected steps ~~of the inversion method are as follows~~include:

1 – Particle size distribution expressed in “equivalent melted diameter” is assumed to be exponential, i.e.:

$$N(D)=N_0\exp(-4D/D_m) \quad (1)$$

where  $N(D)$  is the concentration of particles per cubic meter ( $m^3$ ) and per diameter range, and  $N_0$  and  $D_m$  are the two parameters that characterize distribution.

2 – The top  $h_{max}$  and the base  $h_{min}$  of the layer of solid precipitation are determined;

a.  $h_{max}$  is the maximum altitude of the measured reflectivity profile  $Z(h)$ .

b.  $h_{min}$  is either the altitude of the isotherm  $0^\circ\text{C}$  if the ground-level temperature is positive, or it is ground level if the ground-level temperature is negative.

3 – The profile of the parameter  $D_m(h)$  in the range  $h_{max}$  to  $h_{min}$  is then determined by resolving the following differential equation:



$$\frac{fD_m}{fh} = -0.25k_{eff}aD_m^{b-5} 10^{-18}Z + \left( \frac{1}{6} \frac{fZ}{Zfh} \right) D_m \quad (2)$$

where:

- $Z$  is the radar observable to be inverted in  $\text{mm}^6\text{m}^{-3}$ ;
- $D_m$  is in meters (m);
- $a$  and  $b$  are coefficients specific to particles of the “aggregate” type, equal respectively to 35184 and to 3.16 on the basis of the observations of J.D. Locatelli and P.V. Hobbs, *Fall speeds and masses of solid precipitation particles*, J. Geophys. Res., 79, 2185 - 2197 (1974), the subject matter of which is incorporated herein by reference;
- $k_{eff}$  is the coefficient of effectiveness of the aggregation process to be adjusted (the value  $k_{eff} = 0.3$  seems correct).

4 – The integration of (2) takes place from the top, where the boundary condition is expressed by fixing the total number of particles  $n_T$  (or the number of ice-forming nuclei activated at the top of the cloud). It is possible to take  $n_T(h_{max}) = 10^6 \text{ m}^{-3}$ , which makes it possible to express the boundary condition  $D_m(h_{max})$  as:

$$D_m(h_{max}) = 25.4 \cdot 10^{-18} (Z(h_{max})/n_T(h_{max}))^{1/6} \quad (3)$$

5 – Once the profile  $D_m(h)$  from  $h_{max}$  to  $h_{min}$  has been determined, the profiles of the other parameters of interest are computed by the following expressions:

- a. Profile of  $N_0$ :  $N_0(h) = 102 \cdot 10^{-12} Z(h)/D_m(h)^7$
- b. Profile of the total number of particles  $n_T(h)$   $\{(\text{in m}^{-3})\}$ :  $N_T(h) = 102 \cdot 10^{-12} Z(h)/D_m(h)^6$
- c. Profile of the ice water content  $IWC(h)$  (in  $\text{g/m}^3$ ):

$$IWC(h) = 1.25 \cdot 10^{-12} Z(h)/D_m(h)^3$$

d. Profile of the solid precipitation rate  $R(h)$  (mm/h equivalent melted). By using the terminal fall velocity determined by Locatelli and Hobbs for aggregates:

$\{v_T=107.6 D^{0.65} (D \text{ in m})\}$ ,  $R(h)$  is expressed by:

$$R(h)=4.698.10^{-10}Z(h)/D_m(h)^{2.35}$$

[0019] The following description relates to another ~~version~~selected aspect of ~~the~~a method of processing for determining the precipitation rate.

[0020] For rainfall, the algorithm used is the ZPHI algorithm which is the subject of ~~French Patent Documents~~ FR\_98/00714 and FR\_01/09206, the subject matter of which is incorporated by reference.

[0021] For solid precipitation, the ~~novel algorithm that has just been developed is the subject of the following description~~applies.

[0022] ~~This algorithm~~The method for estimating the precipitation rate for solid precipitation ~~belongs to the~~includes a class of “profiler” algorithms ~~in that it inverts the vertical profile of reflectivity measured in the ice, so as to extract therefrom the vertical profile of the solid precipitation rate.~~

[0023] The ~~algorithm~~method applies ~~essentially to~~ stratiform precipitation. It considers that the ice-forming nuclei are activated only at highly negative temperatures, i.e., at the top of the cloud. The ice crystals formed at high altitude settle and grow as they fall, either by sublimation of the ambient saturating water vapor, or by collection and freezing of supermelted cloud water droplets, or else by random aggregation of their collisions with other ice crystals. Of the three growth processes, only aggregation changes the ice particle concentration. The algorithm is based essentially on a simplified description of the aggregation mechanism. ~~The~~Selected steps ~~of the inversion method~~ are as follows:

Particle size distribution expressed in “equivalent melted diameter” is assumed to be exponential, i.e.:

$$N(D)=N_0\exp(-4D/D_m) \quad (1)$$

where  $D$  is the equivalent melted diameter of the ice particle;

$N(D)$  is the concentration of particles per  $m^3$  and per diameter range; and

$N_0$  and  $D_m$  are the two parameters that characterize distribution.

The top  $h_{\max}$  and the base  $h_{\min}$  of the layer of solid precipitation are determined;

$h_{\max}$  is the maximum altitude of the measured reflectivity profile  $Z(h)$ .

$h_{\min}$  is either the altitude of the isotherm  $0^\circ\text{C}$  if the ground-level temperature is positive, or it is ground level if the ground-level temperature is negative.

[0024] The profile of the parameter  $D_m(h)$  in the range  $h_{\max}$  to  $h_{\min}$  is then determined by resolving the following differential equation, whose solution can be determined analytically:

$$\frac{\partial D_m}{\partial h} = -24 \frac{4^d k_{\text{eff}} J(b,d) a}{\Gamma(4+d) \Gamma(\hat{a}-1)} Z D_m^{b-(\hat{a}-2)} + \frac{1}{(\hat{a}-1)Z} \frac{\partial Z}{\partial h} D_m \quad (2)$$

where:

$$J(b,d) = \int_0^\infty \exp(-4x) x^b \left[ \int_0^x \left[ x'^d - x'^d \right] \exp(-4x') dx' \right] dx$$

describes the collision frequency;

$Z$  is the radar observable to be inverted in  $\text{mm}^6\text{m}^{-3}$ ;

$D_m$  is in  $m$ ;

- $a$ ,  $b$ ,  $c$ , and  $d$  are coefficients dependent on the density law  $F(D)$  for ice particles, which law is assumed to vary at  $D^{-\gamma}$  (where  $\gamma$  can take values in the range 0.25 to 1.1 depending on the type of particles). These coefficients are drawn from Mitchell's

Theory (Journal of Atmospheric Sciences, 53, 12, 1996), the subject matter of which is incorporated by reference, for representing the following power laws:

$v_t(D) = cD^d$  (where  $v_t$  is the terminal fall velocity of the particle of equivalent melted diameter  $D$ ):

$A = aD^b$  (where  $A$  is the effective cross-section of the particle of equivalent melted diameter  $D$ );

With coefficients depending on frequency and ~~on~~ as a function of ( $D$ ), representing by a power law the relationship between reflectivity (measured parameter), the concentration of the particles, and their mean equivalent diameter:

$$Z = \dot{a}N_0D_m^d$$

$k_{\text{eff}}$  is the coefficient of effectiveness of the aggregation process to be adjusted (the value  $k_{\text{eff}} = 0.3$  seems correct immediately above the isotherm  $0^\circ\text{C}$ ).

[0025] The integration of (2) takes place from the top, where the boundary condition is expressed by fixing the total number of particles  $n_T$  (or the number of ice-forming nuclei activated at the top of the cloud). It is possible to take  $n_T(h_{\text{max}}) = 10^6 \text{ m}^{-3}$ , which makes it possible to express the boundary condition  $D_m(h_{\text{max}})$  as:

$$D_m(h_{\text{max}}) = \left[ \frac{1}{4\dot{a}n_T(h_{\text{max}})} \right]^{\frac{1}{\hat{a}-1}} \quad (3)$$

[0026] Once the profile  $D_m(h)$  from  $h_{\text{max}}$  to  $h_{\text{min}}$  has been determined, the profiles of the other parameters of interest are computed by the following expressions:

Profile of  $N_0$ :

$$N_0(h) = \frac{Z(h)}{\dot{a}D_m(h)^{\hat{a}}}$$

Profile of the total number of particles  $n_T(h)$   $\{(\text{in m}^{-3})\}$ :  $n_T(h)=0.25N_0(h)D_m(h)$

Profile of the ice water content  $IWC(h)$  (in  $\text{g/m}^3$ ):

$$IWC(h)=(1.2272)10^4 N_0(h)D_m(h)^4$$

Profile of the solid precipitation rate  $R(h)$  (mm/h equivalent melted):

$$R(h)=(1.885)10^6 c \frac{\Gamma(4+d)}{4^{(4+d)}} N_0(h)D_m(h)^{(4+d)}$$

Vertical profile of the Doppler velocity  $V_D(h)$  (in meters per second (m/s)), given by a power law dependent on density  $\rho(D)$ :

$$V_D(h)=pD_m(h)^q$$

[0027] Because of the dependency of the coefficients relative to the density law  $F(D)$ , the retrieval of the precipitation rate depends critically on the parameter  $\gamma$ , as shown by ~~Figure~~Fig. 7. The density law thus constitutes a key parameter.

[0028] By operating in vertical firing, it is possible to measure the Doppler velocity  $V_D(h)$ , and to compare it with  $V_D(h)$  computed by the algorithm. The Doppler velocity profile is discriminating, as shown by ~~Figure~~Fig. 8. By successive adjustments, it is thus possible to determine the parameter  $\gamma$  of the law  $F(D)$  for which consistency between  $V_D(h)$  as computed and  $V_D(h)$  as measured is achieved. ~~Figure~~Fig. 4 shows an example of a profile inverted by the algorithm (in ~~this~~that example, the isotherm  $0^\circ\text{C}$  is at ground level). ~~Figure~~Fig. 5 shows the curves resulting from application of the aggregation model and ~~of the~~a conventional model, making it possible for the profile of  $D_M$  resulting from the inversion of  $Z$  by the aggregation model to be compared with the conventional estimator.

[0029] ~~Figure~~Fig. 6 shows the curves of the profiles as a function of altitude (m) above the isotherm  $0^\circ\text{C}$ . It enables the profiles of  $N_0$  and  $n_T$  resulting from  $Z$  being inverted by the aggre-

gation model to be compared with the conventional hypothesis and observations. ~~Figure~~Fig. 7 shows the profile of R resulting from Z being inverted by the aggregation model compared with the conventional estimator. ~~Figure~~Fig. 8 shows the sensitivity of the retrieval of the equivalent participation rate (mm/h) to the particle density law  $\rho(D) \propto D^{-\gamma}$ . ~~Figure~~Fig. 9 shows the sensitivity of the retrieval of the vertical Doppler velocity to the particle density law  $\rho(D) \propto D^{-\gamma}$ .